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The Meteorological Office — a ten-year perspective

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Summary

The Meteorological Office's main responsibility is to provide meteorological services (including weather forecasts and advice regarding weather and climate) to defence, civil aviation, shipping, other government departments, public bodies, the media, industry and commerce and the general public. It is widely perceived as one of the leading national meteorological services in the world, a position which results from the integrated nature of the Office's activity and remit (especially the integration between defence and civil activities), from the way in which the Office has concentrated its effort into key areas and from the quality of personnel the Office has been able to attract. This is an appropriate time to review the activities of the Office and to present the major components of its programme over the next ten years.

In the international sphere, close co-operation between national meteorological services must be maintained, as must the principle of the free exchange of data and products between them.

Future developments in observations will be governed by the need to improve data quality and coverage, and the need to improve the cost effectiveness of data acquisition through a programme of automation. Of particular importance will be the improvement of space observing techniques both in improved hardware in space and also in better methods of data retrieval and interpretation.

A major equipment replacement programme is planned. Replacement of the central computer, the Cyber 205, will also be required before the end of the decade.

Expansion of the Office's repayment services is an important task during the next few years. Much of this expansion will occur through co-operative arrangements with other bodies, especially in industry and commerce.

The Office's programme of research and development will be strongly geared to the improvement of its operational products. Developments can also be expected in the way in which the human forecaster uses computer aids, the man–machine mix, in producing his products. Other important areas where the Office needs to pursue research to maintain expertise are those concerned with climate and atmospheric chemistry. Steps are being taken to enhance the co-operation between the Office and research groups elsewhere, particularly in the universities.

1. Introduction

During my first two years in office as Director-General, I have become familiar with the wide-ranging work of the Office both in operations and research, and with the variety of associations the Office has with the outside world both nationally and internationally. I believe, therefore, it is a good time to review the activities of the Meteorological Office and to present the primary goals of the Office and the major components of its programme over the next ten years. I shall first deal with the general matters of objectives, philosophy and organization, and then turn to more particular scientific and technical matters. Finally, I shall address the question of resources. Relevant background details regarding the activities of the Meteorological Office can be found in its Annual Report.

2. Objectives and philosophy

2.1 *Functions of the Meteorological Office*

The functions of the Meteorological Office as laid out in recent Annual Reports provide a broad statement of the Office's responsibilities. Its main responsibility is to provide meteorological services to defence, civil aviation, shipping, other government departments, public bodies, the media, industry and commerce, and the general public. The provision of meteorological services includes the provision of weather forecasts for the surface and the upper air, and the provision of information or advice concerning all aspects of weather or climate, especially as they affect human activity. The Office's remit is therefore a very broad one. In recent years, as forecasts have become considerably more accurate, as the amount of relevant information has increased and as the means for its dissemination have become more readily available, the demand on the Office for more and better information of all kinds has increased manyfold, an increase which is likely to continue unabated for some years into the future. Some of the problems this poses, together with some of the opportunities created, are now considered.

Regulation. Because of the broad nature of the Office's responsibilities and because the Office is not governed by any statute or charter, questions are often asked regarding how the Office's activities are regulated. Regulation occurs in four ways.

(a) There is the normal continual internal review of activities within the Office itself in response to scientific and technical possibilities on the one hand and to customer pressure and perceived demand on the other, limited always by the resources available and the need to be cost effective.

(b) There is the annual process in the Ministry of Defence in which the Office's assumptions, and requirements stemming from these, are rigorously examined.

(c) There are the results of a number of reviews and investigations of the Office's activities. Of these the most important (and the most thorough) is the Rayner Resource Control Review* (RCR). Its recommendations as modified and approved by ministers form, in most regards, a firm basis for the way forward for the Office.

(d) There is the regular scrutiny of the Office's programme by the Meteorological Committee with its broad scientific and customer representation.

These four mechanisms together form quite a tight regulation of the Office's activities while leaving room for appropriate initiative and evolution.

Provision of services. In taking any view of the Meteorological Office it is important to understand the basic means by which the services are provided. The source of most of the information provided to customers and users comes from the generation of weather forecasts that cover the whole globe and which extend to a few days ahead; these are made twice every day. The tools required to generate them are world-wide observations, global communications and large computer models of the atmospheric circulation. This central operation (including the UK's share of the collection of world-wide observations) takes up nearly two thirds of the total resources of the Office. Without it, none of the Office's major customers could be provided with the services they require. This fact is recognized by the inclusion in the listed functions of the Meteorological Office of the organization of meteorological observations and the collection and dissemination of meteorological information (both in concert with other national meteorological services), the provision of meteorological training and the carrying out of research in meteorology and geophysics, all of which are required if the main responsibility of the provision of a wide range of services is to be properly discharged.

* Ministry of Defence; Report of the resource control review of the Meteorological Office, 1983, London, HMSO.

2.2 *A leading national meteorological service*

The Meteorological Office is widely perceived both nationally and internationally as a leading national meteorological service in the world in the quality of its forecasting products. The performance of the Office's forecasting models and the skill of its forecasters bear very favourable comparison with any other service. Yet, as has been pointed out by the RCR, this excellence is achieved at modest cost, in fact a lower cost per caput than for comparable countries in the developed world. It is worth at the start of this review asking what are the reasons for this pre-eminence and cost-effectiveness. I put forward three main reasons: integrated nature of the Office's work, concentration of effort and quality of personnel.

Integrated nature of the Office's work. Operational meteorology in the United Kingdom is concentrated in the Meteorological Office. This is not the case in many countries where operational meteorology for defence is separated from that for the civil sector, or where services for commerce and industry are separated from services to the public. The integrated nature of the work of the Meteorological Office not only avoids unnecessary duplication but also provides the opportunity for the staff to acquire experience over a broader range than would otherwise be possible, and broad experience translates significantly into forecasting skill.

Concentration of effort. Over the years, the Office has concentrated its effort into key areas, and ensured that its work in research and development (R and D) has been followed through into operational products. Good integration (achieved largely through regular interchange of staff) between the services side and the R and D side of the Office has ensured that there has been a continuous flow of information from the service side about the requirements and a similar flow from the R and D side regarding what is feasible. This concentration of effort and close integration of activity has been particularly true of the Office's numerical modelling. Scientists in the Office were some of the first to recognize the potential of numerical modelling for forecasting and were able, single-mindedly, to develop appropriate models and to acquire the computing capacity to run them effectively for operational purposes. The small proportion of the Office's resources devoted to R and D has, therefore, been effectively used. I say small — it is small (currently less than 12%) in proportion to the whole of the Office's resources and very small in comparison to what has been devoted to similar activity elsewhere, for instance in the USA (see section 6).

Quality of personnel. The Office has been fortunate in achieving over the years a high level of attractiveness to some of the best graduates in physics and mathematics. This situation is in no small part due to the enthusiasm with which my predecessor, Sir John Mason, publicized the exciting science going on in the Office, not least through the high quality lectures he gave in academic institutions throughout the United Kingdom. The high profile given to the quality of science being carried out in the Office has attracted some of the best intellects to the research side of the Office, many of whom, after a significant research career, have turned their abilities and energies to furthering the services and applications side of the Office's work. I consider it high priority to continue to recruit and retain the highest quality graduates — a task which has become more difficult as the Civil Service has become less attractive compared with industry or research abroad.

Cost-effectiveness. Meteorological Office customers continue to demand high quality information. Defence certainly requires the best information possible not only because war remains a highly weather-dependent activity but also because the best use of flying training time must be made whilst

maintaining aircraft safety. The public at large also welcome a good forecast — the improvement in accuracy of public forecasts over recent years has been noticed and appreciated. Further, in the area of repayment services, the commercial edge possessed by the Office is highly dependent on the quality of its products. If these were not perceived as the best available, the demand for Meteorological Office services and the amount which customers would be prepared to pay would be much reduced. For instance, the fact that a significant proportion of the world's airlines demand our global wind products (and pay additional handling and communication costs for direct computer access to them) because they are perhaps 10% more accurate than other available products, demonstrates the value that they put on quality.

However, one cannot talk of excellence without considering its cost — value for money is also important. I have already pointed out that the quality of the Office's products has not been bought at a high price but is due to the quality of its personnel and to selectivity in its programme. The cost of providing excellence as opposed to mediocrity is not high; it is of the order of a few per cent (probably less than 10%) of the whole budget of the Office. I believe, that so far as global modelling and forecasting skill is concerned, we will be able to maintain a leading position without an undue increase in cost providing that:

(a) we maintain our quality of personnel,

(b) we continue to maintain our integrated service, and

(c) we continue to capitalize on our ability to exploit profitably the full capacities of the most advanced computers.

An implication of the integrated operation is that the Meteorological Office should remain an integral part of the Ministry of Defence — the Office's largest single customer. It is unfortunate that the simple arrangement with an integrated Meteorological Office as part of the Ministry of Defence has commonly been seen in recent years as untidy or illogical. Numerous reports have been commissioned to look into the situation. Of these the RCR is by far the most thorough. While considering a number of alternatives, it supported unequivocally, in the interest of efficiency and cost effectiveness, the present arrangement. I am convinced that any other arrangement would tend to lead to a break-up of the service (see section 5.1) and would certainly lead to inefficiency and increased cost because of the multiplication of technical, financial and administrative support.

3. The international context

3.1 *International arrangements*

World Meteorological Organization. Operational meteorology is a highly international activity. National meteorological services co-operate through the World Meteorological Organization (WMO), an inter-governmental organization which is often regarded as one of the most efficient of the international agencies. It has a clear organizational and technical remit, and is flexible and pragmatic in the way it pursues its objectives.

The WMO does not itself make observations or produce forecasts, all that is done by national meteorological services. What the WMO does is:

(a) to organize through the Global Telecommunication System (GTS) and the Global Observing System (GOS) the exchange of data, forecasts, analyses and products between national services, and

(b) to stimulate and co-ordinate research, education and technology transfer.

A keystone of the WMO arrangements and agreements is that the exchange of data and products takes place completely freely, an arrangement which has many advantages. Countries, by and large, play their part in the provision of basic observations from their territory or regions of interest. In return, they have free access to the data and products of other services. There is concern in WMO that increasing

commercial pressures might begin to erode these very open arrangements. Along with all other heads of national services, I am keen to see that the close co-operation between services and the free exchange of data and products are maintained. If these were to break down, world meteorology would lose a great deal.

World Area Forecast Centre. A particularly important area of international collaboration in the application of meteorology is the field of civil aviation. The two meteorological services with the most advanced global forecasting models, namely the USA and the United Kingdom, share the responsibility for providing global meteorological information (upper-air winds and significant weather) to the world's airlines for operational and route-planning purposes. This role as a World Area Forecast Centre will become increasingly important as the demand from airlines for more accurate and more timely information increases.

Assistance to small and developing countries. A concern often expressed by small countries and developing countries is that they want to see the benefits of meteorological activity shared equitably between the nations. Such countries, especially those in Africa, have received and are receiving a great deal of help for their meteorological services. For our part, we are using the modest resources available to us to provide appropriate assistance and training especially to countries in the Commonwealth with whom we have close links. For instance, a Conference of Directors of Commonwealth Meteorological Services which is held every 4 years, the most recent in 1985, clearly still serves a useful purpose. We are also taking a lead within WMO in considering new ways in which assistance programmes in meteorology can be financed. Further, we are currently taking steps to make our forecast products more widely available to other national services. Our reasons for these efforts are not just to provide assistance to the developing world; we ourselves require high quality data from these countries. I consider it important, both from the point of view of improvement in the quality of meteorological data and from the point of view of the health of the world meteorological community, that the Meteorological Office, which is widely perceived as a world leader, should also be seen to continue, through the mechanisms provided by WMO, to use its competence and influence for the benefit of the meteorological community at large.

3.2 *Regional co-operation*

A trend of recent years in international meteorology is co-operation between national services on a regional basis. An example of such co-operation is the European Centre for Medium Range Forecasts (ECMWF) whose base is at Shinfield Park, Reading and within which 17 nations are co-operating in the development of forecasts 4–10 days in advance. The achievement of useful accuracy in deterministic forecasting that far ahead will require a great deal of research into the mathematics and technology of computer modelling, into the physics of relevant atmospheric processes and into the requirements for data. The ECMWF is widely recognized as being the leading centre in this field and it is also providing a great deal of stimulation for European meteorology. Over a ten-year period, a substantial increase in the accuracy of medium-range forecasts from the Centre can be anticipated which, from the point of view of the Meteorological Office, should lead to an increase in demand for those commercial services of the Office which are geared to this range.

There are many further examples of European co-operation in meteorology. For instance the geostationary meteorological satellite, Meteosat (through the European Meteorological Satellite (EUMETSAT) organization) and various co-operative programmes in science and technology (COST). The most notable of the COST projects is the linked operational weather radar network and a number of

research projects (e.g. those on mesoscale frontal dynamics and on wave modelling) in which, through the concentration of resources from several nations, a concerted attack on important problems is possible.

A particularly important area where further European collaboration will develop is that of satellite observations. Over the past 25 years the USA have been generous in the way that they had made data available from their satellites, but they now frequently express the view that they are bearing too great a share of the cost. There is a constant threat that the polar orbiting satellite system run by the National Oceanic and Atmospheric Administration (NOAA) might be reduced to a single operational satellite — a reduction which would be particularly disadvantageous to Europe because satellite observations would be lost at a critical time for European services. Various solutions have been proposed to this problem, all of which inevitably mean that nations other than the USA, especially advanced nations, will have to make a larger contribution to the system. A possible way for Europe to assist will come through the Polar Platform which is being proposed as a European contribution to the US Space Station. Operational meteorological instruments could be part of the payload of this platform. The UK contribution to satellite observations is considered more fully in section 4.1.

4. The core operational activity

In section 2.1, I mentioned the core operational activity of the Meteorological Office in the making and the collection of observations, in global communications and in global computer modelling of the atmosphere leading to forecasts with world-wide coverage. The various components of this core activity will be addressed in this section.

4.1 *Observations and instrumentation*

Global data are required not only for global models but also to set the boundary conditions for more limited-area forecasting models (e.g. those giving detailed coverage of the United Kingdom). The world system of data collection and communication is therefore vital to the success of any forecast. It is sensible to ask, therefore, what part the United Kingdom plays in the world system (organized by the WMO and known as World Weather Watch (WWW)) and whether that part is seen as a fair share of the whole. The annual cost of observations to the United Kingdom is about £20 million, about £12 million for conventional observations and £8 million for satellite observations — amounting in total to over 25% of the Office's budget. Conventional observations are concentrated in the land and continental shelf areas of the United Kingdom and the eastern Atlantic Ocean where observations are particularly important in the context of UK weather. We also provide such observations where we have military bases (Federal Republic of Germany, Cyprus, Gibraltar, Ascension Island and the Falkland Islands). In the USA, a similar proportion of the total spent on operational meteorology (approaching $2000 million per annum) goes towards observations including satellites. In absolute terms, however, it is much larger than that of the United Kingdom — about twenty times as large — or over twice as large in proportion to the Gross National Product (GNP). Some other countries, for instance Australia, Canada and Japan, contribute in proportion to GNP somewhat more than the United Kingdom, although many smaller countries contribute considerably less. Therefore, to play our part properly we need, if anything, to increase our contribution to the world acquisition of data.

Guidance for future work on observations and instrumentation arises from two requirements, that of improving data quality and coverage (see section 4.3) and that of improving the cost effectiveness of data acquisition largely through a programme of automation.

Land surface observing network. The next few years will see a significant increase in the deployment of Automatic Weather Stations (AWS). These are important but currently provide only a limited amount of information. There is an expectation that useful automated measurement of cloud base and visibility will be achieved at such stations in the near future but reliable automated measurement of general weather conditions and cloud amount and type has yet to be demonstrated. These latter measurements are an essential input to the forecaster and are mandatory at key observing stations.

Over the next few years, trials of a Semi-Automatic Meteorological Observing System (SAMOS) will take place at military and, hopefully, civil airfields. This system automates as much as possible of the processes of gathering, displaying and communicating meteorological observations whilst requiring the human observer to key only those data which he or she must provide. Thereby some saving in observer time is possible. However, substantial savings in the number of observers required will only be possible when accurate, reliable automatic measurement of all parameters has been achieved. The development and testing of suitable instrumentation for this will take place during the next ten years. Adequate performance will, however, not be easy to achieve and it is unlikely that operational deployment of such instrumentation will begin to occur until the end of the ten-year period covered by this review.

Upper-air observations. Plans are currently underway, in response to the recommendations of the RCR, to deploy a more cost-effective and a more automated system of upper-air observations. It is planned that this will be in place at all upper-air stations before 1990.

Because of the high cost of dedicated weather-ships, the deployment of more cost-effective observing systems over the oceans is under consideration. Upper-air soundings from merchant ships are becoming possible through ASAP (Automated Ship Aerological Programme); free floating buoys again deployed from merchant ships can provide basic surface observations, and automated observations from commercial aircraft are being generated through the ASDAR (Aircraft to Satellite Data Relay) programme. For all of these systems, data are relayed from the observing device in the ship, buoy or aircraft via a satellite link to an appropriate connection to the meteorological network. In setting up all of these programmes, the United Kingdom has played a leading role and is planning to contribute to them as resources become available through the winding down of the weather-ship operation.

Radar and microwave techniques. Relatively new methods of observation which are of increasing importance are those employing radar and microwave techniques from the surface. Radar data are of vital importance for local and short-term forecasting. The recent establishment of an operational weather radar network covering England, Wales and Northern Ireland is a big step forward; the operational value of this data as exploited by the Office, the Water Authorities and other commercial users is apparent. It has also provided essential data for analysis and assessment of the movement of radioactivity in the atmosphere following the accident at the Chernobyl nuclear power station. It can be expected that sufficient support will be forthcoming from other interested bodies and that the radar network can be extended to cover Scotland during the next few years.

Techniques for making observations of wind and temperature above a surface location by vertical radar coupled with passive microwave radiometry have recently been pioneered in the USA and promise to be a valuable addition to the observing system, particularly because of the potential they offer for a dense network of observations important for local and short-range forecasting. A programme of assessment of these techniques has begun in the Office, the expectation being that in a few years' time several 'Profilers' as they are called will be in operational use.

Satellite observations. Plans for the deployment of operational satellite systems during the next ten years are largely in place (satellite plans need to be made a long time ahead). So far as the United Kingdom is concerned the plans assume a continued contribution to operational Meteosat through the European consortium EUMETSAT, and the continued provision of instrumentation for the TIROS-N polar-orbiting series of the USA. The new TIROS-N instrumentation which the Office is developing in co-operation with industry, the universities and the Rutherford Appleton Laboratory (RAL) is part of the Advanced Microwave Sounding Unit (AMSU) which will be incorporated into the TIROS-N payload around 1990. Significant improvement in the accuracy of satellite soundings of atmospheric temperature will result from this instrument.

Important priorities for the future in satellite meteorology are:

(a) the better exploitation of data from existing satellite systems, and

(b) an involvement in the design and planning of future satellite systems to ensure that the plans are soundly based so far as operational meteorology is concerned.

There is a need for the acquisition of satellite data with high horizontal resolution to provide adequately detailed input into the finer-mesh models and to assist in short-term forecasting. The combination of satellite soundings from polar-orbiting satellites (and later hopefully from geostationary satellites, see below) with radar data is potentially very powerful in this regard.

Because of the influence of cloudiness below the satellite on the measurements, there is a problem in maintaining an adequate quality of satellite observations of atmospheric temperature. Work on the improvement of the quality of satellite soundings is being pursued by the Meteorological Office Unit at the Hooke Institute at Oxford. Improved techniques for the assimilation of satellite data into operational models also need to be developed; because of their difference in character from such conventional data there is a long way to go before their full potential is realized.

Regarding satellite instrumentation, because of the growing importance of satellite observations and because of the large potential for carrying instruments into space offered by developments in the space field such as the Space Station and Polar Platform (already mentioned in section 3.2), the Office is working with other groups in the United Kingdom and abroad on investigations into new methods of measuring quantities of meteorological and geophysical interest. For the European Remote Sensing Satellite ERS-1, the Office is assisting in small ways with the Along Track Scanning Radiometer (ATSR) — an instrument for accurate measurement of sea surface temperature being built by RAL — and is also planning to assist with data analysis and interpretation from the wind scatterometer on ERS-1. Data from both instruments will be useful for routine operational purposes. For the future, the Office is helping to define the payload for the Second Generation Meteosat due for launch around 1995 and with others is suggesting suitable instrumentation to be included on the European Space Agency's (ESA) Eureka platform should that be made available for earth observation, and for the polar and other free flying platforms which it is proposed should be associated with the Space Station.

The new arrangements for the management of space activities in the United Kingdom through the British National Space Centre (BNSC) are of considerable importance to the Office. Following on from ERS-1, other government departments are showing a lot of interest in the pursuit, through ESA, of a programme in remote sensing probably associated with the Polar Platform which is expected to be a component of the US Space Station. The Office possesses substantial expertise in the relevant technologies for this programme. The global computer models possessed by the Office will also be an important vehicle for the assimilation of meteorological and oceanographic data acquired in the programme, and for ensuring that the user community receive the maximum benefit from the data. The formation of the Space Centre should provide a mechanism for the United Kingdom to develop a space programme scientifically and technically sound, working for the benefit of the United Kingdom as a

whole (including of course, UK industry) — it should also enable the United Kingdom to play its part in Europe more effectively.

Use of satellite and conventional observations. Constantly in view is the question as to how far satellite observations can replace conventional ones. So far, observations from space have largely complemented conventional data by enabling better coverage in both space and time to be realized, although they lack the detail required particularly in the lower atmosphere for some purposes. Further, so far it has also been necessary to employ conventional observations to calibrate those made from space. As forecasting models become more sophisticated and more detailed, the requirements for data at a higher spatial and temporal density, with better coverage and higher accuracy, will continue to become more severe. It will continue, therefore, to be necessary to exploit to the full both conventional and satellite techniques. Although in small ways there can be a trade-off between satellite and conventional observations (for instance, because satellite observations of atmospheric temperature are now regularly available, most aerological soundings do not need to reach such a high altitude, with some small saving in equipment and in time) it is not likely that during the next decade this trade-off will be very large.

Evaluation of observing systems. A significant effort over the next few years will go into the evaluation of observing systems. This is being planned in co-operation with other nations. However, since few nations possess a global operational numerical model of high quality, it is inevitable that much of the burden of this work will fall on the United Kingdom. The aim is to assess the value of different combinations of observations so far as forecast performance is concerned. It is a difficult task because of the varied character and accuracy of the observations, because of the influences which may be introduced by assimilation procedures and because of the wide variety of forecasts for which the Office is responsible from global upper-air forecasts for airlines on the one hand, to highly specific forecasts for a local area on the other.

4.2 *Telecommunications and data processing*

Forecasters require timely access to observations and products from the numerical models. The data rates from new observational tools such as satellites and radars are many times greater than from conventional observations; there is therefore a requirement for faster methods of data distribution. The amount of data available for distribution continues to increase, particularly from satellites and higher-resolution global forecasting models. Over the past few years the Office has made substantial investment in automated data handling and message-switching systems in its Telecommunication Centre at Bracknell to keep pace with the growth in international exchanges of data and products whilst permitting reductions in manpower. Mini-computer based systems have been successfully introduced at the three Principal Forecasting Offices, with links to Bracknell providing speedy access to data and products. However, communication networks serving outstation forecasting offices are overloaded. Many of these offices do not have access to important products, such as radar and satellite data, and their means for handling and displaying data have not changed significantly for several decades. Also their equipment is obsolete and the efficiency of outstation personnel is seriously hampered through their lack of access to essential data. The potential value of these offices to the public and to the customers they are attempting to serve is not being fully realized.

Weather Information System. A high priority for the Office is to carry through a major equipment replacement programme at outstations serving both civil and military customers. Computer-based

facilities with a local data base, together with a new higher capacity digital communications network, will provide the forecaster with a wider range of timely information and the ability to manipulate it efficiently to generate and issue products which will meet more effectively the needs of his various customers. A prototype of the outstation display system has been developed. Systems will be installed by April 1987 at eight important offices serving the RAF. Design of the communications system is underway. It is proposed that these new facilities, known as the Weather Information System (WIS), will be extended to all outstations over the period 1987–91. A new central processing facility will be developed for handling high resolution digital satellite imagery and generating products suitable for distribution to forecasting offices. A high-speed local network will be provided to improve the efficiency and flexibility of exchange of data and products between various computer systems and communication facilities at Bracknell.

Cyber 205. Current operational numerical forecasting models are run on the Cyber 205 'super-computer' which was installed in 1981. This machine is already fully occupied with forecasting and research tasks. Realization of the potential improvements in forecasting models, including the operational use of a numerical model for very-short-period forecasting, research into long-range forecasting and ocean modelling (including realistic ocean–atmosphere coupling for climate research and to meet Royal Navy requirements) will all require more powerful computing capacity. Current projections are that a computer at least 50 times faster and having appreciably greater capacity than the Cyber 205 will be required in the early 1990s. The Office will be making proposals to meet these expanding requirements in the light of super-computers which may be available. The most cost-effective solution may involve replacement of the Cyber 205 with a next generation machine around 1987, upgrading that to its full capacity in the early 1990s. Software compatability with the Cyber 205 will be a major consideration. It is anticipated that the two IBM 3081Ds (the second procured in 1985) which act as front ends for the Cyber 205 will, with some upgrading of processing power and peripherals, meet the general purpose computing needs of the Office until around 1993.

4.3 *Forecasting*

Forecasting skill has shown a steady improvement over the last 25 years. During the last 5 years or so the accuracy of forecasts up to 5 days ahead has been such that the public and the specialized Meteorological Office customers put much greater reliance than hitherto on the forecasts as a guide to their activities.

This gain in performance has been achieved by progressive improvements in:

(a) the quality and coverage of weather observations, and the ways in which observations are incorporated into the numerical models,

(b) the numerical methods employed in the models and the computing power available, and

(c) the parametrization of physical processes included in the forecasting models.

No improvement on its own can be singled out as the main reason for greater forecasting skill. Many relatively small improvements have all played their part. From the point of view of meteorology as an applied science, it is most encouraging that the consistent inclusion of better physics and mathematics is leading to better forecasts. Although, because of the basically unpredictable nature of some atmospheric processes, there clearly are limits to what will eventually be attainable in forecast skill and forecast range, we are a long way yet from reaching those limits. For these reasons, continued improvements in the three areas mentioned above will form a significant part of the R and D effort of the Office over the next ten years.

Very short-range forecasting. The highest priority in forecasting R and D is being given to the very short range — the first 12 hours — partially because the demand for detailed information, high accuracy and precise timing in the short term is apparent from many of our customers, not least from Defence, and partially also because research on medium-range forecasting techniques is being carried out elsewhere, notably at the ECMWF (see section 3.2).

The improvement of forecasting in this very short range is being attacked from two sides — through the provision of better observations which has already been addressed in section 4.1, and through the development of a mesoscale model which has a much higher horizontal resolution (about 15 km instead of 75 km for what is called the fine-mesh model). The mesoscale model is currently quasi-operational and is already proving of value. It is, however, still at an early stage of development and its full potential will not be realized for perhaps 5 years. During the development period, not only will it be necessary to put a lot of effort into understanding the behaviour of the model but also it will be necessary to learn the optimum way in which the variety of relevant observations can be assimilated into it.

Extended-range forecasting. Some R and D will also continue into forecasting for the extended range (10 days up to about 1 month) beyond the limit at which deterministic forecasting is possible, but still at a range where there is good hope that general circulation models have some predictive capability regarding the general character of weather patterns. Should significant predictability be possible at this range, demand for extended range forecasts would be high. Research in this area is also closely connected with the Office's investigations into climate and the causes of climate change (see section 6).

Man–computer interaction. An area currently receiving a lot of attention and which will see substantial changes over the next decade, is that of the man–computer interaction involved in forecasting. The practice of forecasting provides excellent examples of many of the techniques in information technology which are currently receiving a large amount of emphasis. A number of the activities connected with model input or output currently carried out by human operators will be taken over by appropriate computer routines, leaving the forecaster free to exploit his expertise and experience more fully in other ways. Careful consideration will be given to the computer aids which can be provided to enable the best use to be made of the skill and experience of the human forecaster both in coming up with the best possible forecast and interpreting that forecast in terms of the needs of the wide variety of users.

5. Meteorological Office services

In this section I review likely developments in the four main areas of Meteorological Office services, namely; defence, civil aviation, the free public service and repayment services.

5.1 *Defence services*

The Meteorological Office serves the RAF, the Army Air Corps and other Defence establishments through its forecasting offices at airfields and other locations. These offices are staffed by civilian personnel who, by taking a full part in operational activities and exercises, demonstrate their capability to provide a fully effective service under peacetime conditions, periods of tension and of transition to war. An important reason for the Meteorological Office remaining as an integral part of the Ministry of Defence is the effectiveness of these arrangements which are advantageous both to the Armed Services (in that they provide forecasting personnel of high competence and with wide experience) and to the Meteorological Office (in that they provide a wide remit and excellent training).

Defence outstations urgently require better access to the range of forecasting products, data and aids now available at Bracknell. As was mentioned in section 4.2, this is planned; Defence outstations will be the first to be supplied with display units of WIS. A lot of the emphasis at Defence outstations is on low-level local, short-range forecasting, the improvement of which is the aim of many of the developments mentioned in section 4.

The requirement for meteorological services laid down by the Air Staff clearly includes the requirement for a forecasting presence at operational RAF stations and for face-to-face briefing. With the increased sophistication of aircraft and weapon systems the requirement for the local on-the-spot expert is likely to be strengthened. However, in addition to the deployment of WIS into RAF stations there is an urgent need for better ways of disseminating data between the various locations within an airfield, especially at sites where there is hardened accommodation.

Army ground operations are becoming even more weather sensitive and senior Army personnel are increasingly realizing the tactical value of accurate and timely weather information over and above that already required for the Army Air Corps. A statement of the Army's requirements is currently being prepared which will form the basis of the Office providing a modest but effective service.

The Office will continue to work closely with the Royal Navy. Plans are under way to connect their establishments more effectively to the Office's data and products through the use of WIS. The Office is also co-operating with the Royal Navy in ocean-modelling research. Modelling the ocean has much in common with modelling the atmosphere, although the computing demands for ocean modelling tend to be greater (a smaller grid length is required to cover comparable dynamical systems in the ocean which are of smaller scale than those in the atmosphere). Through the enhanced ocean-modelling capability which is being developed for the climate research programme, the Office is beginning to assist in developing models appropriate to the interest of the Royal Navy. Because of the close link between the atmosphere and the ocean (atmospheric forcing drives the ocean circulation) it is appropriate that the research on coupled ocean–atmosphere forecast models be carried out on the Meteorological Office computer.

Further, in the Defence Services area, the Office will continue to become involved in providing support and advice to a variety of organizations and projects, for example to NATO, Civil Defence and USAF establishments in the United Kingdom.

5.2 *Services for civil aviation*

During the last few years, substantial changes have taken place within the organization of world-wide meteorological services for civil aviation. These are now centred on the new World Area Forecast System (WAFS), for which Bracknell is one of the two world centres (see section 3.1), and the arrangements are beginning to work well. The improved upper-wind information now available to airlines by direct link from the Bracknell computer is proving very valuable indeed to airlines — savings of the order of 1 to 2% of the total airline fuel bill (i.e. £60 million out of £4000 million for the airlines employing Bracknell data) have been quoted to us as resulting from the use of Bracknell information for route planning, rather than information available from other sources*. During the next 5–10 years, more comprehensive flight and route planning will be introduced by world airlines with an accompanying requirement for higher accuracy in upper-air wind forecasts and more reliable predictions about weather situations likely to affect landing schedules at airfields. Research and development directed towards these requirements will continue, as will research relevant to other

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* In 1986 a team from the Meteorological Office were awarded the Royal Society Esso Energy Award for their work for aviation forecasting, see *Meteorol Mag*, **116**, 1987, 29–31.

particular aviation problems such as icing and fog formation. The Meteorological Office will be looking at ways of improving the means of communication of this information to airlines as well as ways of improving the forecasts.

During the next few years substantial changes will occur in the way forecast information is disseminated at airfields, especially the smaller airfields where the introduction of automation will improve the service considerably. Streamlining of the service to general aviation will occur as more automated means of communication with pilots are introduced by the Civil Aviation Authority.

5.3 *The free public service*

A basic dilemma is the requirement on the one hand to provide the best possible service to the general public through the media and other information channels, and on the other hand to meet a significant part of the Office's costs through selling services on repayment. The better the Office does the former, the harder it is to do the latter. A balance therefore has to be drawn. The RCR suggested how the 'free' service might be defined, a definition subsequently modified after discussion by Ministers. Because of the continuously changing nature of the content and quality of the Office's products and of the requirements of customers, a continual appraisal of this balance needs to be made. Being aware of what services are possible, the Office needs to be sensitive to the needs and desires of the public at large while also having an eye for commercial areas where substantial returns to the Office (and therefore to the taxpayer) might be achieved.

Apart from special requirements in emergency situations, the policy is to continue to restrict the provision of individual forecasts but to concentrate efforts on the dissemination of forecast information through the press, radio, television, videotext, recorded telephone services and the like. For these outlets there is a varying degree of recovery of the cost of communication or presentation.

Some of these services are provided centrally, some regionally. Concentrations of the provision of the regional services is now in the Weather Centres and the Main Meteorological Offices (MMOs); virtually no public services are now provided from RAF airfields and Defence outstations except in emergency.

During the past few years a review of the work of the Weather Centres in different areas has been carried out and some rationalization had been carried through or is planned. Work in south-west Scotland has recently been reorganized and concentrated in one Weather Centre in Glasgow. A similar operation has been carried out for the Manchester area and plans for south-west, central southern and south-east England are currently being formulated. Relocation and reorganization of the Aberdeen and Birmingham Offices are also being looked into. The development of the Weather Centres is discussed further in section 5.4 covering repayment services.

Although, as I have said, the situation needs to be kept continually under review, I do not expect the scale of material provided for the free public service or the extent of services for which a subsidy is provided to change significantly during the next few years. However, the efficiency of dissemination of forecast information will expand considerably to the benefit of both the 'free service' and repayment services.

5.4 *Other repayment services*

A priority of the Office in recent years has been the expansion of its repayment services — a priority which was endorsed by the RCR. A marketing branch has been set up and over the last 2 years receipts from customers outside civil aviation have increased by over £1 million. The possibilities for further expansion are good.

A fundamental question which needs to be raised is whether it is appropriate for the Office to engage in these repayment services. Why not, as in the USA, pass the information over to the private sector and

allow them free rein? There are various arguments why the present mixed arrangement is sensible and effective.

(a) There is a significant return to the taxpayer.

(b) The value of the integrated service — the quality of the product is improved by having those responsible for the products also engaged in selling them to customers. Forecasters and advisers are kept more in touch with the customer.

(c) Weather Centres established in major centres to service the general public and civil aviation can utilize their staff for part of the time for repayment services, many of them essential to the well-being of commerce and industry, thereby making better use of their time and resources.

(d) The quality of the service can be maintained — the private sector has a quality product by which to judge its service.

(e) The private sector (even in the USA) is unable or unwilling to invest in the infrastructure required to maintain a quality service over the whole range.

Given that the market for repayment services can be expanded, how should that expansion be pursued. There are three possible options: to sell relevant data to companies in the private sector, to set up joint commercial arrangements with appropriate companies or to expand the Office's commercial activities to meet the demand.

Selling relevant data. The opportunities for selling data as such are very limited largely because much of the data is available elsewhere. The WMO's Global Telecommunication System network, on which flows a large proportion of meteorological data and products, is becoming increasingly accessible at no charge or very small charge to private companies primarily through access points in the USA where a policy of free access to all data exists.

Joint commercial arrangements. The setting up of joint commercial arrangements fits the Office's position very well and was strongly recommended both by the RCR and by the Sharp/Hansford* report. A number of arrangements can be envisaged in which the Office co-operates with firms having particular commercial expertise or skill, in marketing or in information technology. Combining skills and 'know-how' in this way under arrangements where both parties have a stable and long-term commitment, should enable much greater returns to be forthcoming and should ensure that the returns are shared out in an equitable way.

Expansion of commercial activities. The final option is that the Office should expand its commercial infrastructure so that it can provide for itself outlets for its products. Although there are clearly opportunities here it is neither desirable or politically acceptable for there to be large growth in the Office in the area of commercial infrastructure. The Office needs to strike the right balance and pursue selectively those areas of commercial activity which fit in well with its other activities and responsibilities.

An important area of activity which is ripe for exploitation is that of cable and direct broadcast television and viewdata services. Here facilities need to be set up not just for providing data and products but to provide packaged forecasts via text or through live presenters in forms which are attractive to the variety of needs of the companies involved.

So far in this section I have addressed new possibilities for commercial activity. Significant room also exists for the development of existing repayment services especially through the Weather Centres. As a first means of improving their efficiency, up-to-date technology is required, a need which has already

* Sharp, K.J. and Hansford, J.; The Meteorological Office financial management, 1985, London, HMSO.

been mentioned in sections 4.2 and 5.1. The Public Services Branch and the Marketing Branch are also looking carefully at activities in the Weather Centres with a view to increasing their effectiveness, for instance more attention is being given to those areas where our specialized and expert services can provide the greatest financial return. It is planned to increase the commercial awareness of the Weather Centres and their marketing skill by providing them with financial targets which will make them more cost conscious. Similar considerations apply to the future of the Meteorological Office Advisory Services, both as part of the free public service and as a component of the repayment services.

6. Research and development

One of the listed functions of the Meteorological Office is to carry out research in meteorology and geophysics. Without any qualification, this is an enormous remit and could absorb any amount of resource. In the USA, for instance, nearly $400 million per annum is spent on research in meteorology and atmospheric physics. On the civil side, $70 million is spent through NOAA, $60 million through the National Aeronautics and Space Administration (NASA), and $110 million through the National Science Foundation (NSF). Equivalent figures in this country are £8 million by the Meteorological Office, £3.5 million by the Natural Environment Research Council (NERC) and about £2 million by the Science and Engineering Research Council (SERC). It should be pointed out that care should be taken in interpreting these figures; some (such as the figure quoted for the Meteorological Office) include a substantial amount of development — others refer almost entirely to fundamental research. Nevertheless, the figures clearly show the degree to which there are overwhelmingly more resources available for research in the USA.

What, therefore, is the Meteorological Office's role in research and how does it fit in with the rest of the national and international scene? What should be the size of the research programme and what are its priorities for the next ten years?

6.1 *Research programme*

The reasons for the Meteorological Office's research programme are:

(a) to provide support for, and the basis for improvement of, the operational services provided by the Office, and

(b) to provide a basis for continuing expertise in the areas of the field where the Office is required to provide expert advice.

About three quarters of the total Research and Development effort and resources are directed towards improvements in forecasting and operational services. They have, however, already been discussed in section 4. Therefore I turn to those areas where the Office needs to maintain special expertise. Climate is the most important of these. Expertise is required on the climate of the past, especially the most recent (i.e. the last 100 years or so during which a reasonable coverage of accurate observations has been available), and on the future trends in climate from a month or two ahead to tens or perhaps hundreds of years ahead. Of particular interest and importance are the possible effects of man's activities on climate. The tools for this climate research are firstly the large climate data base which the Office maintains for a variety of reasons and secondly global numerical models of the atmosphere and ocean circulation.

Because knowledge of the state of the ocean is probably as important as knowledge of the atmosphere for climate beyond a few months ahead, a high priority over the next decade will be the development of ocean models coupled to the atmospheric models. The topic of ocean modelling is in its infancy and is likely to develop rapidly. The Office has taken the initiative in setting up a small ocean modelling unit,

which NERC is also supporting, in the Hooke Institute for Atmospheric Research at Oxford. Although only small in size it is amongst the foremost groups in the subject in the world at the present time.

Another significant area where advice is required from the Office is in atmospheric chemistry, especially as related to pollution (e.g. acid rain) — an area which demands expertise not only in atmospheric chemistry but in atmospheric physics and dynamics (including that related to the boundary layer). Although the Office's contribution here cannot be large, enough work has to be carried out within the Office to maintain adequate expertise. Because of the integrated nature of the Office's programme and the wide range of data, knowledge and experience possessed by the Office, the maintenance of a small team working in a topic such as atmospheric chemistry is mutually beneficial so far as the rest of the Office is concerned and can be carried out very cost-effectively.

A major facility available to the Office is the Meteorological Research Flight Hercules aircraft. It contributes to many of the areas we have already mentioned, in particular to the development of adequate parametrizations of physical processes (e.g. the boundary layer, cloud–radiation interaction, turbulence, etc.) for mesoscale dynamics and cloud physics investigations, and to atmospheric chemistry and pollution research. The potential of the array of instruments now fitted to the aircraft, together with the sophisticated data recovery system recently installed, is considerable and a decade of exploitation can be looked forward to. During this period, to ensure the best use of the facility, the generation of well-focused projects carried out jointly with other laboratories in the United Kingdom and overseas will be important. Because the Hercules is so well instrumented — possibly better than any other meteorological research aircraft in the world — there is no difficulty in developing co-operation, but this co-operation clearly has to be of the right kind. Collaboration by university scientists in the aircraft projects and in the analyses of data will be particularly welcomed.

A central theme underlying much of the Office's research programme is that of the development of numerical models which are required on a wide variety of scales ranging from a particular part of the boundary layer, perhaps a few kilometres across, to global circulation models covering the whole extent of the atmosphere. Despite the large range and the varied purposes for which models are developed, all employ the same basic physics and fluid mechanics, and a great deal of commonality exists between them. This is an illustration of an important feature of the Office's research programme — namely its integrated nature. Work in almost any part of the programme has influence on a number of other programme areas. In any review of the programme, therefore, it must be seen as a whole. In this regard the Research Sub-Committee of the Meteorological Committee performs a valuable function.

6.2 *Co-operation*

The main part of the Office's research programme is of necessity rather well defined and directed. It is therefore of importance that there is a lively research community outside the Office, especially in the universities with whom the Office can interact. Those of us working in the subject also feel that meteorology and geophysics are excellent academic disciplines possessing a great deal of intellectual challenge, demanding a lot of technical ingenuity and having the advantage of being thoroughly anchored in the real world. I am keen, therefore, to see the Office use its influence to encourage the development of viable, effective research teams in the universities. I shall be working along with the NERC and the University Grants Committee (UGC) to this end. A particularly useful means of co-operation between the Office and universities are the CASE (Co-operative Award in Science and Engineering) studentships. These can be valuable in any subject — perhaps the most valuable is in areas of rather fundamental science where joint supervision by an academic scientist and an Office expert can be especially rewarding to all the parties involved. It is important for the Office, by such means or otherwise, to keep abreast of fundamental developments and important also that a few of the Office's

scientists should achieve individual merit status when they can spend some of their time pursuing fundamental problems and ideas.

As an example of joint activity with a university, the arrangements at the Hooke Institute at Oxford which have already been mentioned are worth describing in more detail. Within the Meteorological Office Unit at the Institute there are research groups in satellite meteorology, ocean modelling and stratospheric dynamics — each of which is tied very closely to the work in its parent Meteorological Office Branch. Although their work is formally under Meteorological Office management, their broad programme of work is also agreed with the other members of the Institute (i.e. the University and NERC) through the Institute Steering Committee, the intention being that there should be very close collaboration between those working within the Institute to whatever parent body they belong. By this means it is hoped to avoid the problems which have been associated with NOAA — University Joint Research Institutes in the USA where the work of the Institutes has tended to become almost entirely divorced from the operational work of NOAA, to their and NOAA's detriment. The Hooke Institute has got off to a good start; clear benefit is accruing to the Office in that students and others within the Institute are becoming involved in Meteorological Office programmes. The Institute is already recognized as one of the world's leading centres in meteorological and oceanographic research.

Co-operation in research internationally is vital if the Office is to remain in a leading position. It is also necessary because many problems are too large to be solved by a single nation alone. Of the current international research programmes relevant to the Office, the most important is the World Climate Research Programme (WCRP) in which members of the Office are thoroughly involved.

6.3 *Size of the research programme*

The final question to ask regarding the Office's R and D programme is whether it is of the right size. In terms of resources compared with similar programmes in the USA it appears to be very poorly supported indeed. On the other hand, compared with the total budget of the Office, the proportion of resources devoted to R and D (about 12% — compared with 16% for the USA) is not so grossly out of line.

The Office's R and D programme must continue to be highly selective regarding those areas which it tackles and must be consistent with the requirements I have outlined. Within these areas the teams must be viable in order to be effective. Savings in staff and resources in recent years — the research budget has fallen from about 16% in 1979 to just under 12% at present during a period when activity in the subject elsewhere has increased dramatically — have resulted in some activities being marginally viable. The decline in resources for R and D has now been halted. I believe, in order for the standard to be maintained and to pre-empt a drift of research scientists abroad, over the next five years it should be allowed to revert back to the 1979 figure.

7. Resources

7.1 *Cost benefit*

Before looking at resources, it is appropriate to consider the question of cost-benefit. Questions are often asked regarding the cost-benefit of the services provided by the Meteorological Office. For the Office's work related to Defence it is difficult to be quantitative; it might be noted however that military activity is, and is likely to remain, highly weather sensitive — as are many of the weapons systems employed by all the Services. A comparison between the annual cost of the Meteorological Office services to Defence with the possible losses due to ignorance of weather elements — for instance it is only slightly more than the value of one Tornado aircraft — shows that it is potentially a very cost-effective service. Regarding other areas of the economy served by the Office, again it is not easy to be precise. A

study of the value of meteorological services was carried out by Mason (1966)*. Crude but plausible estimates were made of benefit in different areas of activity. His conclusion that the overall cost-benefit ratio lies between about 10 and 20 is probably conservative; to my knowledge it has not been seriously disputed. The benefit, although real, is in many areas spread so broadly that only a small proportion of it is realizable in terms of revenue.

7.2 *Resources required*

I now turn to consider what resources will be required in the light of the priorities I have stated, i.e. that the Meteorological Office should maintain its leading position, improve and expand its services, and increase its commercial activity and return.

Personnel. The Meteorological Office complement fell from about 3650 in 1974 to 3200 in 1979 and was further reduced to 2700 in 1984 — a drop of 26% during the ten-year period. The introduction of automation in communications and data handling, together with contracting out, has made most of this reduction possible during a period when the range and quantity of services provided by the Office has shown a substantial increase as has its income from repayment services. A further 7% reduction to about 2400 net of loans and secondments is planned by 1988.

By 1988 most of the savings possible from the current programme of automation and from the contracting out of services will have been made. Some small growth in the numbers of personnel involved in the repayment services will be necessary during the next few years if the potential growth in that area is to be realized. There should, therefore, be a levelling off in the complement at about the 1988 figure — small savings due to further automation being fed into increased customer activity.

A trend in the personnel structure which will continue is that the proportion of senior staff will increase. Increases in efficiency due to automation or otherwise, or savings of staff due to contracting out of services, imply the loss of junior not senior staff. A leaner more professional and cost-effective complement of staff eventually means more staff at senior grades relative to junior ones.

There is currently a significant secondment of Meteorological Office staff to industry — numbers should increase if appropriate contractual arrangements for joint activities with commercial concerns are introduced (see section 5.4). I believe a great deal more exchange between the Office, universities and industry would be healthy and beneficial. Such statements have frequently been made about the Civil Service as a whole but implementation has so far been disappointing due, I believe, to over rigid but long-standing Parliamentary rules surrounding Civil Service appointments and unrealistic Treasury attitudes to allowances and secondary remuneration. The status and effectiveness of Government service, and of the other sectors involved, could be improved enormously if such exchange were commonplace.

A continuing important activity concerning personnel is that of training. Already, through the College at Shinfield Park, Reading and otherwise, the Office is very involved with training. I anticipate that during the next decade there will be increasing emphasis here, including more frequent scientific and technical 'updating' courses for forecasters and a broader range of training, e.g. in marketing skills.

Accommodation. The central accommodation occupied by the Meteorological Office, the London Road building at Bracknell will continue to serve as the Office's headquarters site because of the large investment already made in specialized operational facilities. Increased automation is expected to lead to further centralization on Bracknell and some transfer of staff from shift-working operation tasks to

* Mason, B.J.; The role of meteorology in the national economy, *Weather*, **21**, 1966, 382–393.

day work. The London Road building is already overcrowded and conference room facilities are below standard. Additional accommodation is urgently needed at or very near to the London Road site. An assessment of the long-term requirements is being carried out jointly with Property Services Agency (PSA). This is likely to lead to proposals to reduce the number of sites in the Bracknell area used for supporting activities, although at the cost of re-building some specialized facilities, e.g. the technical archives.

The other main site where development is likely to occur is at Shinield Park where the Meteorological Office College and the ECMWF are accommodated. At that site, those parts of the domestic facilities and residential accommodation currently provided by temporary buildings are in urgent need of replacement.

Resources as a whole. It is interesting to note that despite the increased commitments of the Office and the improved forecasting products, the gross Meteorological Budget has not changed much in real terms in recent years. Since 1979, during a period when the MOD budget as a whole has risen by nearly 20%, apart from the cost of Meteosat (the development and early operations of Meteosat were paid for by the Department of Trade and Industry and the Meteorological Office assumed responsibility for new satellites and their continued operation in 1983) the gross cost of the Office has fallen by about 4% in real terms, the charges to CAA have fallen by 2% in real terms and the income from repayment services (other than CAA) has risen by 100% in real terms.

During this period of a reduction in resources, the Office has concentrated on ensuring that adequate resources have been available to maintain its central forecasting capability at a high level. Very little resource has, however, gone into improving the technical capability of the outstations; there is, therefore, considerable catching up to be done so far as the outstations are concerned (see section 4).

Concerning provision for equipment and facilities, priority must be given during the decade to:

(a) ensure that meteorological personnel serving Defence, aviation, the public service and repayment customers have efficient access to, and the ability to manipulate and utilize easily, the data and products that are available from the central facility, so that their time and expertise is most effectively employed,

(b) ensure that adequate computing resources continue to be available within the central facility, and

(c) ensure that improvement in observational capability continues and that the United Kingdom continues to play its proper role in meteorological observation especially in satellite-based observations.

During the next ten years a progressive increase in the receipts from repayment services (other than from other government departments) is planned. Current receipts amount to about £5 million per annum. A target increase of 10% per annum has been set which would lead to receipts of £12 million per annum by 1995. During the first few years the increased revenue from repayment services will be required to provide resources for the developments I have listed above. The net cost of the Office in real terms would remain roughly constant, therefore, over the first few years but would fall by the end of the period by about 5%. At that time approximately half of the increased revenue from repayment services would go towards increased facilities and equipment for the Office, the other half into reducing the Office's net cost. That there should be a sharing of increased revenue of this kind was, in fact, suggested by the RCR.

Finally, I turn to the methods for allocation and control of resources. I consider it a high priority to achieve a more rational arrangement for the allocation of resources from MOD to the Office. Although I have responsibility for the formulation and execution of the Meteorological Office programme, I do not have any formal responsibility for resources. It is generally agreed that the Meteorological Office should have responsibility for resources delegated to it; strong recommendations to this effect have been made

by both the RCR and the Sharp-Hansford report. The next few years will see substantial progress in this direction.

8. Concluding remarks

I believe that the next ten years will be both exciting and rewarding for the Meteorological Office as developments in both science and technology enable us to improve the quality, the effectiveness and the range of the services we are able to offer to our varied customers.

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Persistent anomalous circulation and blocking*

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Summary

The most extreme weather conditions over the United Kingdom often arise when the normal progression of Atlantic weather systems is halted by blocking patterns characterized by the splitting of the jet stream into two branches; one passing to the north of the country and the other passing to the south. In summer these may give persistent spells of fine weather (e.g. 1976) or in winter are usually accompanied by severe cold (e.g. February 1986). The predictability of the atmosphere on the monthly time-scale is likely to be strongly dependent on those physical mechanisms responsible for the maintenance and stability of blocking patterns. For this reason, substantial effort has been invested recently in the study of blocking dynamics, with the proposal of several new theories. In this paper some of these new developments are examined.

1. Introduction

The study of blocking underwent a resurgence of interest in the late 1970s with the appearance of some new(?) theoretical ideas and with the greater availability of high quality global data sets. Since then many of the properties of blocking known to forecasters have found expression in highly simplified models of the atmosphere and are better quantified in terms of new diagnostics. Nevertheless it is probably also true to say that our ability to forecast blocking in the extended range sense (e.g. 7 days–1 month) has not benefitted noticeably from these studies.

There are two particular types of anomalous circulation that need emphasizing. The first and most important type is the familiar regional blocking for which the anomalous circulation is predominantly confined to a certain longitude sector and occurs in geographically preferred regions. It typically has a time-scale of the order of 2 weeks and tends to be most frequent at certain times of the year (e.g. western Europe in spring). The second type is what can be referred to as the 'severe winter' pattern. It is epitomized by the northern hemispheric circulation patterns of winters such as 1947 and 1962/63 when the axes of the major jet streams were much further south than normal and low wave number planetary waves were of very large amplitude. These anomaly patterns are even more persistent than blocking and, as in the 1962/63 winter, last longer than 2 months.

The main characteristics of blocking patterns are sketched briefly in section 2 and the concept of potential vorticity is introduced. Steady-state solutions of certain approximated equations of motion are discussed in section 3 in order to clarify how an isolated block dipole can remain stationary when

* Lecture note from a series of lectures entitled 'Dynamical Processes in Meteorology' given as part of the 1986 Advanced Lectures (Meteorological Office, 15 September–3 October 1986).

embedded in westerly flow. In section 4, the old idea that blocking is some sort of resonance phenomenon is examined with a beta-plane model of barotropic flow. Green (1977) drew attention to the possible role of momentum transfer induced by travelling weather systems in the maintenance of blocking anticyclones against surface friction. This transient eddy theory has developed and gained much acceptance since then and is outlined in section 5. Finally in section 6, a hemispheric scale circulation anomaly pattern, which sometimes accompanies blocking, is identified and is defined as the 'severe winter' pattern. In such winters, the surface wind is anomalously easterly throughout much of the mid-latitude belt.

2. The blocked flow type

Blocking 'highs' are characterized by a region of warm air with higher than ambient pressure which extends upwards from the surface to the lower stratosphere. Within them the winds are generally light and the tropopause is higher than average. They are usually accompanied by a somewhat smaller region of low pressure with the opposite properties. This combined 'dipole' is embedded in a diffluent flow field and tends to fluctuate in amplitude and phase (longitude) with the passage of travelling weather systems (Fig. 1). There is often a tendency for high pressure cells to collapse only to rebuild further to the west causing an overall westward translation of the pattern.

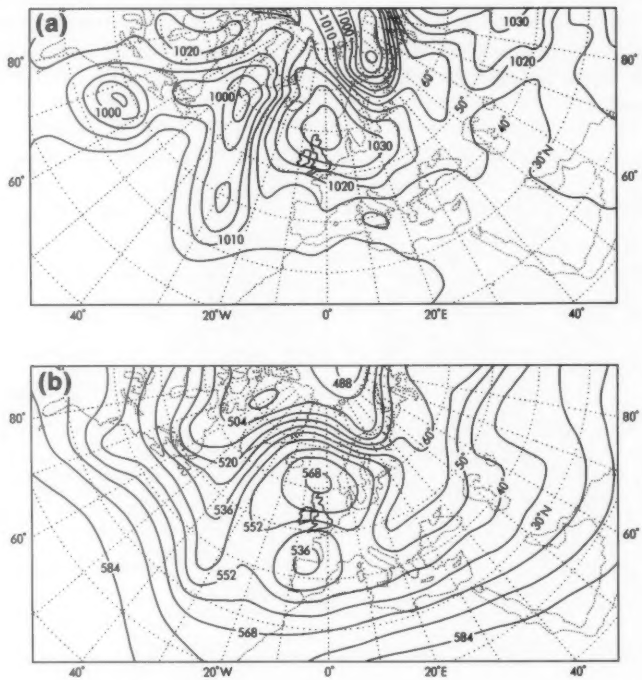


Figure 1. Surface pressure (mb) field (a) and geopotential height contours (dam) of the 500 mb surface (b) for 12 GMT on 15 February 1983.

Much of our theoretical understanding of large scale atmospheric dynamics is derived from approximate forms of the equations of motion which involve the conservation of some quantity following the motion of an air parcel, e.g. absolute vorticity conservation in barotropic flow. In three-dimensional stratified flows, the vorticity vector of an air parcel may be changed by a number of different mechanisms though, at large scales, principally by vortex stretching. Nevertheless, the scalar product of the vorticity and vector gradient of potential temperature (all divided by the density) is conserved without approximation for adiabatic frictionless flow. This quantity, known as the potential vorticity, provides a valuable link between simplified theoretical models involving analogues of this conservation principle and analyses of real atmospheric motion which may be carried out using the unapproximated quantity. For instance, many phenomena described by the two-dimensional, barotropic equations with latitudinal variation of the Coriolis parameter can be related to real upper tropospheric flow dynamics by interpreting absolute vorticity as potential vorticity, though only when the latter is computed on isentropic surfaces (Hoskins *et al.* 1985). Since potential temperature and potential vorticity are conserved for adiabatic, frictionless flow, the evolution of the field of potential vorticity on an isentropic surface gives a visual indication of air-mass transport; in other words it is a tracer and provides a valuable means of studying the interaction of 'blocking pattern' flows with transient weather systems.

A dynamically significant aspect of the blocked flow field is the reversed potential vorticity gradient (from the normal poleward gradient) as is clearly portrayed by isentropic analyses of Ertel potential vorticity (Shutts 1986). Potential vorticity within the blocking anticyclone is low relative to the ambient flow but high in the accompanying cut-off low further south (Fig. 2). As the following section demonstrates, this dipole arrangement enables the pattern to remain stationary in the presence of a background westerly flow.

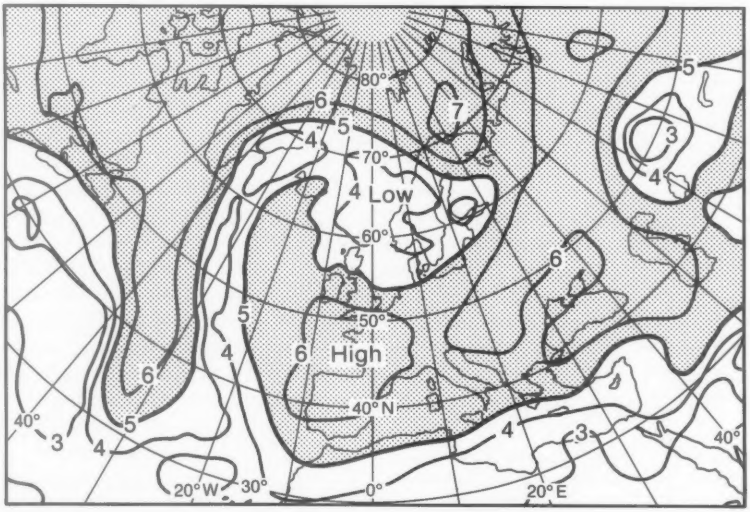


Figure 2. Contours of the Ertel potential vorticity (arbitrary units) calculated on the 320 K isentropic surface for 12 GMT on 15 February 1983. The contour interval is variable so as to enhance the detail in the potential vorticity field where gradients are small. The shaded regions are of high potential vorticity and represent stratospheric air.

3. Free-mode model

Studying sequences of synoptic charts frequently gives the impression that changes in weather type are often accompanied by an abrupt change in the configuration of the planetary-scale flow and a new quasi-equilibrium pattern set up. Such behaviour is characteristic of some idealized non-linear systems containing quasi-equilibrium or 'attractor' points. The free-mode approach to representing blocking flow patterns involves finding time-independent solutions to approximated forms of the equations of motion and examining their sensitivity to governing parameters.

Perhaps the simplest free-mode model with any relevance to blocking is the vortex doublet of classical hydrodynamics embedded in a uniform flow. For a purely barotropic, incompressible and two-dimensional fluid on an f-plane (the 'dishpan' case) fluid parcels conserve their vorticity. The vorticity associated with a point vortex at a position $\mathbf{r}_0$ in the (x, y) plane is zero everywhere except at $\mathbf{r}_0$ where it is effectively infinite. The tangential velocity associated with such a vortex is inversely proportional to the distance from the vortex core. Two point vortices of opposite sign (though equal circulation strength) self-induce a translational movement of the vortex pair in a direction at right angles to their dipole axis and with a speed inversely proportional to their separation. The doublet can be rendered stationary by adding to this solution a uniform opposing current (Fig. 3).

This solution is restricted to systems with no spatial variation in background rotation, i.e. no planetary beta effect. Stern (1975) showed how dipole solutions (named Modons) could be constructed for the beta-plane case and McWilliams (1980) used the equivalent barotropic equations to obtain a stationary Modon solution which serves as a model of blocking (Fig. 4). In contrast to the vortex dipole whose pressure is infinite at the vortex points, the Modon has a physically reasonable pressure distribution everywhere. Various extensions of these barotropic models to the baroclinic case have been made though, as yet, no primitive equation solutions have been found. Of course, real atmospheric blocking is never time-independent and these solutions should at best be regarded as a zero-order description (in the language of perturbation theory) of the phenomenon.

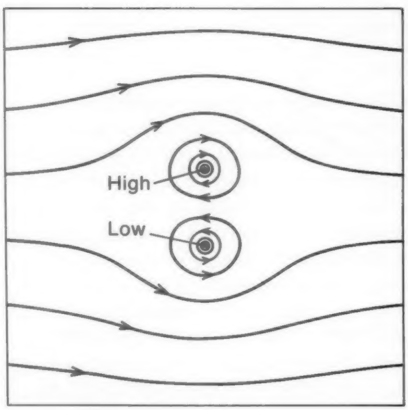


Figure 3. Streamlines of a stationary vortex doublet embedded in uniform flow.

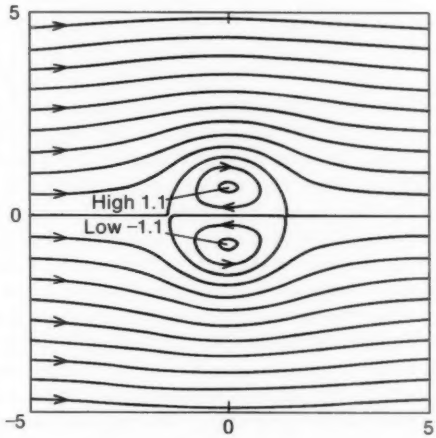


Figure 4. Streamlines of a stationary equivalent barotropic 'Modon' taken from McWilliams (1980).

4. Resonance theories

The idea that blocking may be a manifestation of some kind of internal resonance is old and difficult to trace back to the originator. As a simple example of the principle, consider the barotropic absolute vorticity equation

$$\frac{\mathrm{D}}{\mathrm{D}t}(\zeta+f) = F \qquad \dots\dots\dots\dots\dots\dots\dots (1)$$

where ζ is the vorticity, f is the Coriolis parameter and F is some unspecified source of vorticity due, for instance, to vortex compression associated with flow over mountains. In terms of the non-divergent stream function ψ defined such that $u = -\partial\psi/\partial y$ and $v = \partial\psi/\partial x$, equation (1) becomes

$$\left(\frac{\partial}{\partial t} + \frac{\partial\psi}{\partial x}\frac{\partial}{\partial y} - \frac{\partial\psi}{\partial y}\frac{\partial}{\partial x}\right)\left(\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2}\right) + \beta\frac{\partial\psi}{\partial x} = F \qquad \dots\dots\dots (2)$$

where $\beta = \mathrm{d}f/\mathrm{d}y$ is assumed constant. Consider a purely sinusoidal forcing function F such that

$$F = F_0 \sin kx \cos \mu y$$

where k and μ are wave number vector components. Now look for stationary solutions for ψ involving a constant zonal flow component U such that

$$\psi = -Uy + A \cos kx \cos \mu y$$

and where A is constant. It can be shown that the non-linear terms (terms in A^2) cancel and that

$$A = \frac{F_0}{k[U(k^2+\mu^2) - \beta]} \cdot \qquad \dots\dots\dots\dots\dots\dots (3)$$

From equation (3) it can be seen that waves satisfying Rossby's stationary wave formula

$$k^2 + \mu^2 = \beta/U$$

will be resonant in the sense that this inviscid theory predicts an infinite amplitude response.

Accepting the assumptions of this model, it is difficult to see why the atmosphere is not perpetually resonant since the Fourier spectrum of F will always contain some contribution near to the stationary wave number. The analysis is complicated in general by the non-uniform spatial variation of the background wind with height as well as horizontally. The existence of resonant modes then hinges crucially on whether or not Rossby wave energy can be dynamically 'contained' by, for instance, strong westerly winds in the stratosphere. Lateral containment is more difficult to realize since stationary Rossby waves have 'critical lines' (where $U=0$) in the sub-tropics which tend to absorb wave energy.

When the flow is not precisely uniform, the non-linear terms do not cancel and a perturbation analysis is required to establish the relationship between A and U, given k and μ. It turns out that the equation to be solved for this non-linear case is analogous to that of the anharmonic oscillator (Trevisan and Buzzi 1980). The resonance curve (A against U) now folds over and no finite value of k gives an unbounded response (Fig. 5). Instead, for a range of values of U, high and low amplitude responses are possible. There is an interesting analogy here between the dynamics of the finite amplitude pendulum and these weakly non-linear flows when Uk is interpreted as an angular frequency of oscillation, i.e. $2\pi/$(oscillation period experienced by a parcel).

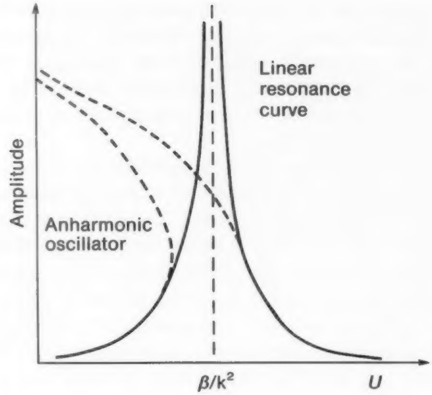


Figure 5. The steady state amplitude of a disturbance forced by barotropic flow over orography plotted against the uniform speed (U) of the current. The solid curve indicates the linear response when the orography is sinusoidal and the basic flow has uniform speed. The dashed curve is the modified response when certain non-linear terms are included.

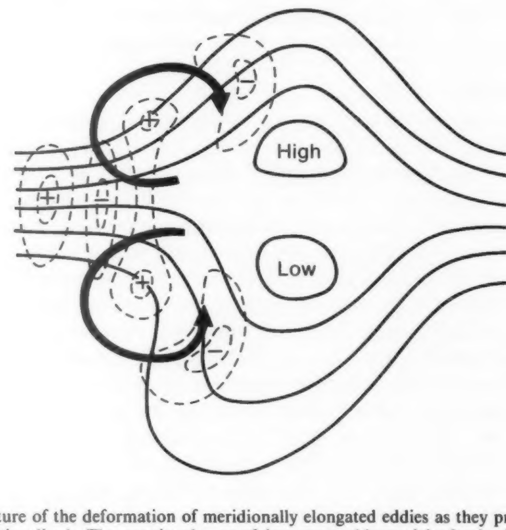


Figure 6. A schematic picture of the deformation of meridionally elongated eddies as they propagate into a split jet-stream region upstream of a blocking dipole. The associated sense of time-mean eddy vorticity forcing is indicated by the black arrows.

5. Transient eddy-forced models

The characteristic diffluence and jet-stream splitting associated with blocking causes transient baroclinic waves to become deformed immediately upstream of the block. The resulting anomalous local fluxes of vorticity and heat (Fig. 6) lead to a time-mean dipole vorticity source orientated so as to reinforce the block dipole pressure pattern (Shutts 1983). Although this conceptual model is incomplete

in the sense that it only describes the nature of the time-averaged forcing function of, for instance, equation (2), it can be studied in the context of a time-dependent barotropic model. There is a growing consensus of opinion that the resonant forcing of local non-linear free-mode patterns by their interaction with transient eddies is the essential mechanism at work in blocking. The geographical distribution of blocking is then controlled by the long quasi-stationary wave pattern forced by orographic and land–sea thermal influences.

A particular problem with the conceptual eddy forcing model is that no clear distinction between eddy and block can be defined in practice. During the lifetime of a single blocking episode only two or three eddy 'events' may contribute to the forcing of the block. The definition of eddy as the deviation from a time–mean value is barely useful and is frustrated by the movement of the blocking pattern during the period. An alternative is to dispense with the block–eddy decomposition of the fields of motion and take a Lagrangian view, for which trajectories of air parcels are the main interest. On the time-scale of a few days, the adiabatic assumption is not grossly in error for upper tropospheric flow and isentropic analysis provides a useful tool for studying air movement. Two conserved quantities (for adiabatic, inviscid flow) are useful to plot on isentropic surfaces: Ertel potential vorticity and mixing ratio. By looking at sequences of potential vorticity maps plotted on a chosen isentropic surface, the injection of high or low potential vorticity air into the block by transient eddies can be seen. Ideally, the block would be characterized by an inner region where air is trapped as a pair of counter-rotating cells of high and low potential vorticity as in the Modon. The slow spin-down of this dipole by surface friction coupled with radiative cooling would be offset by the intermittent injection of 'fresh' high and low potential vorticity brought about by transient eddies. This can be seen to happen in the sequence shown in Fig. 7. For a full account and diagnostic analysis of this blocking episode see Shutts (1986).

6. The 'severe winter' pattern

In contrast to the usual concept of blocking, the 'severe winter' pattern is a hemispheric circulation anomaly with a strong zonally-averaged component. Fig. 8 shows the sea-level pressure and 500 mb height anomalies over the northern hemisphere for February 1947, and highlights the characteristic dominance of anomalous high pressure in latitudes north of 50° N with a ridge into the mid-west of the United States and with anomalously low pressure extending across the north Pacific and Atlantic. The implied geostrophic wind anomaly is easterly almost everywhere between 50° and 60° N, and Siberian air extends well into Europe. A brief perusal of monthly mean sea-level pressure anomaly charts, such as those stored in the Synoptic Climatology Branch of the Meteorological Office, shows that this hemispheric pattern tends to occur quite frequently, though it is not necessarily associated with severe winter conditions in the British Isles, due to minor local differences. Furthermore, empirical orthogonal analyses of real data and a 15-year general circulation model integration have both revealed that this pattern dominates the interannual variation at sea-level and 500 mb (Lau 1981).

Since this type of anomaly is hemispheric, fairly zonal and of long time-scale (1–2 months) it should be regarded as a change in the *modus operandi* of the general circulation rather than an anomalous Rossby wave pattern. As for normal circulation types, transient eddies probably play an important role in maintaining this type of anomalous flow. Changes in the distribution and intensity of the major atmospheric heat sources (Palmer and Owen 1986) could also play an important part in supporting an anomalous pattern such as this, though it would be difficult to distinguish cause and effect.

7. Concluding remarks

There is a growing consensus of opinion that blocking and circulation anomalies are primarily nearly free-mode flow structures excited by their interaction with travelling weather systems. Even so, their geographic location, seasonal dependence and interannual variability are probably controlled

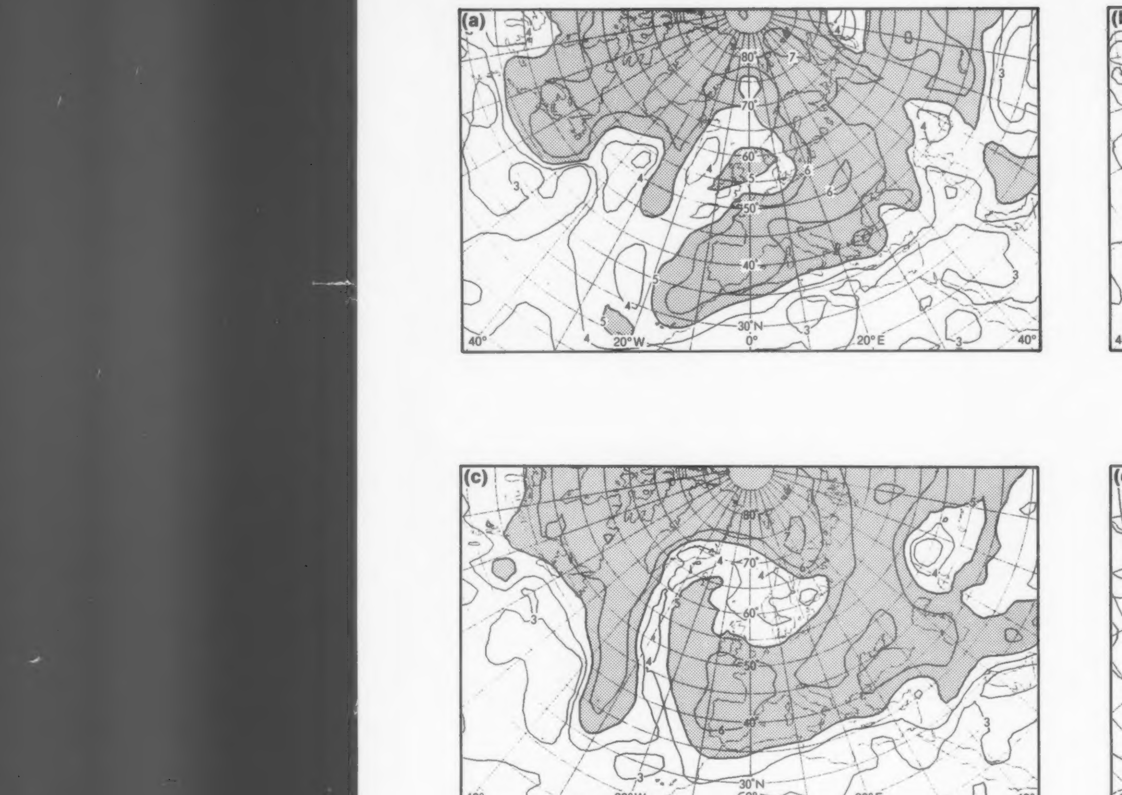
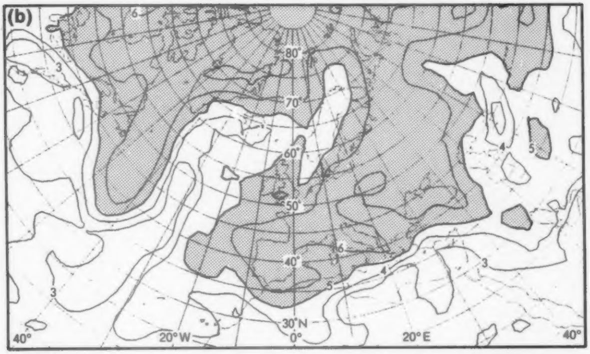
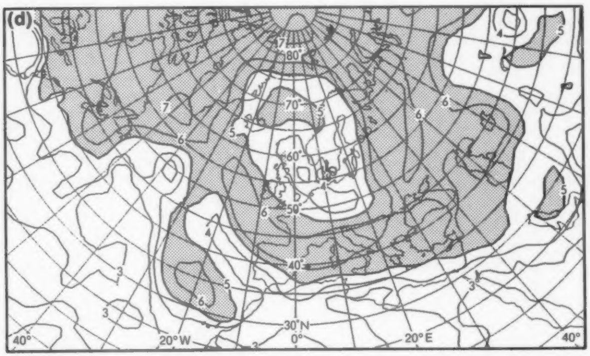


Figure 7. Ertel potential vorticity (arbitrary units) maps for 12 GMT on (a) 13 Februa
northern hemisphere, plotted on the 320 K isentropic surface. The areas with values g





ruary, (b) 14 February, (c) 15 February and (d) 16 February 1983 for part of the
ies greater than 5 have been stippled.

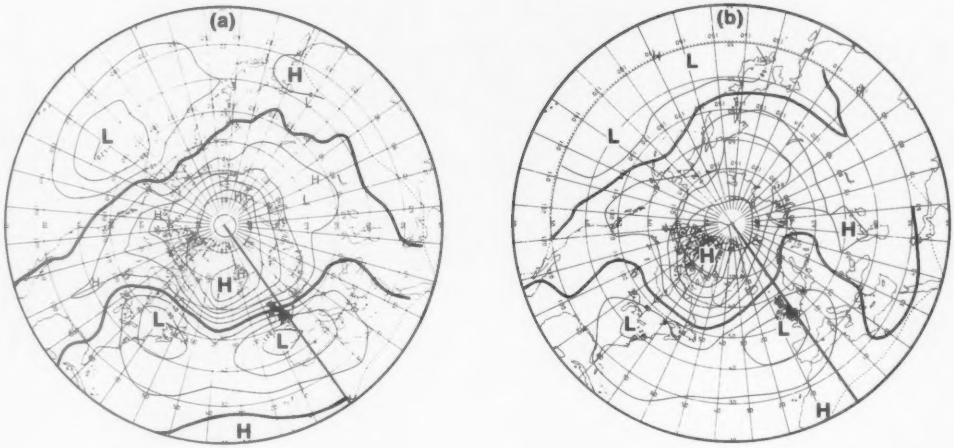


Figure 8. Anomalies of (a) surface pressure (tenths of mb) and (b) 500 mb geopotential height (m) for the northern hemisphere (north of 20° N) during February 1947. Isopleths are drawn at 4 mb and 60 m intervals respectively.

indirectly, through the planetary-scale circulation pattern, by the prevailing distribution of diabatic heat sources and sinks. These, in turn, may be determined to a large extent by the distribution of sea surface temperature, surface ice and snow, soil moisture,etc. Given the slow time-scale of change associated with the above surface properties, there is a hope that blocking episodes may be forecast a month or so ahead if a sufficiently strong causal link exists between heat sources and planetary scale circulation.

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A forecaster's life in the fifties

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Summary

Some experiences of a junior forecaster at various outstations in the United Kingdom and Hong Kong during the period 1951–63.

I joined the Office in 1951 as a direct entrant Assistant Experimental Officer on the magnificent salary of £360 per annum. It wasn't bad pay in those days when lodgings, even in London, could be had for £2 per week including all meals at weekends. After a few weeks at Finningley, I went on one of the first forecasting courses to be held at the new Training School at Stanmore.

After surviving the great smog of 1951, I went back to Finningley as a trainee forecaster. Not for long though as I had 18 postings in my first 3 years. That first posting ruined the best short-term fog forecasting technique I ever developed. Finningley always fogged out 1½ hours after Lindholme. Where did I get posted to from Finningley? Yes, Lindholme!

I spent 3 years on the 'north-east circuit' of RAF stations: Finningley, Lindholme, Leconfield, Driffield, Full Sutton, Cranwell and Acklington to name but a few. Communications consisted solely of teleprinters in those days, no FAX and no satellite pictures. We did have a routine reconnaisance flight out into the Atlantic — code-named Bismuth — done by Shackleton aircraft of Coastal Command. If the teleprinter broke down there were two possible back-ups; if you were very lucky an RAF wireless operator could be found to take down the short wave Morse broadcast, otherwise it was a case of ringing round other offices and collecting bulletins by phone. I remember one assistant who could actually plot the observations on to the chart while they were being read over the phone, but he was an exceptionally fast plotter. All charts were hand plotted at every station and every forecaster had the pleasure of drawing up his own chart plotted in red and black ink on decent paper. The charts I remember most vividly were on a winter evening in early 1953. I was struggling to fit the isobars in the Scottish area of the chart when an off duty pilot came in to see 'how things were'. I had to admit I was out of my depth but felt something dreadful was going to happen. It was the night of the east coast floods which eventually led to the setting up of the storm-tide warning service.

Upper-air charts were drawn by hand and the 1000–500 mb thickness analysis was produced by 'back-gridding' from a 1000 mb and 500 mb chart on a light table. Forecasts were duplicated by the incredibly crude process of jellygraph. The forecast was written or typed with a special backing carbon. It was then placed on a tray of gelatine and the carbon image was absorbed by the gelatine. Blank forecast forms were then pressed on the gelatine face down and peeled off with a copy of the forecast on them.

In 1955 I was posted to Hong Kong. The RAF had an airfield there with an army co-operation squadron of Vampires. Being such an outpost we did not have any modern communications like teleprinters; just our own observation and anything we could persuade the local civil airfield (Kai Tak) to dictate over the telephone. It didn't matter all that much because the Vampires, even at take off, hadn't enough fuel to reach the nearest diversion anyway. Thus the main object was to make sure that no aircraft were airborne when local conditions deteriorated below landing limits. Sudden deteriorations were almost always due to showers and fortunately I had access to an ex-army radar known affectionately as 'Zippy' from its acronym MZPI (Microwave Zone Position Indicator?). Zippy was

powerful enough to pick up the leading and trailing edges of showers out to a range of 40 miles. We gained quite a reputation with Kai Tak because of the ability to produce short-range forecasts of the onset and cessation of showers.

The main event of the day was the afternoon pilot-balloon ascent. In autumn, given clear skies, low-level westerlies and high-level easterlies we always tried for a minimum of 30 000 feet. With daily practice one soon became adept at working out the wind and coding up the PILOT at the same time as following the balloon, so the PILOT was ready for transmission as soon as the ascent was finished. As an extra handicap we used to try our hand out with a tail balloon (a large sheet of coloured paper hanging from the balloon by a measured length of thread). The angle subtended by the tail could be used to calculate the height of the balloon.

The meteorological unit also provided support for the Royal Artillery in Hong Kong; calibration shoots once a year and Meteors for practice shoots as required. Meteors were pilot-balloon ascents coded as mean winds over layers of the atmosphere, rather than at standard levels, through which artillery shells would pass during their flight. Calibration shoots required double theodolite ascents every 30 minutes; no chance of calculating the winds at the same time as the ascent, and after a days shooting it was well into the night before we had all the results available.

While on temporary duty at Kai Tak I had the privilege (?) of a forecasting duty which covered the passage of a typhoon directly over the airfield. There were winds to well over 100 knots (the anemometer broke under the strain so we never knew what the strongest gust was), then about 20 minutes of eerily calm conditions followed by howling winds which were now 180° different from the original direction. Meteorologically not an experience to be missed, but on almost any other grounds to be avoided if at all possible.

Forecasting typhoons was not easy in those days since there was no satellite information. As soon as a typhoon warning was issued, any of the few observing ships within hundreds of miles of the forecast track started steaming away at full speed. If a typhoon reached the Phillipines it created so much damage we lost communications at the critical time. The only accurate information came from a group of dedicated American airmen in a weather squadron based, I think, on Guam. They used to fly into the centre of a typhoon at least once a day to provide an accurate fix. By the time I was involved it was a high-level penetration with a dropsonde in the centre. Prior to dropsondes, I was told they had made low-level penetrations with an ascent in the centre; a very dangerous and at times fatal procedure, although they had the satisfaction of knowing that many lives were saved as a result of accurate information on the movement of typhoons.

Kai Tak duties involved a lot of route forecasts which meant drawing pictorial cross-sections and giving a personal briefing for each individual flight (no significant weather charts or spot winds in those days). We used to do half-route ROFORs (coded route forecasts rather similar to TAFORs but with changes specified by position rather than time) for each route, the destination airfields doing the other half. Making the two ROFORs match in the middle was sometimes more of an artistic problem than a meteorological one. Kai Tak in those days had much too dangerous an approach for night landings so a lot of aircraft used to land just before dusk, stay overnight then take off at dawn. On a night duty it took about six hours to draw the forecasts, so the duty forecaster used to take a last look at this charts around midnight and then drew steadily throughout the rest of the night to be ready for briefings starting around 0600 local time.

For most of my time in Hong Kong the charts looked rather bare because they had no Chinese observations plotted on them. This was a political problem because China was still officially represented in the United Nations (and therefore WMO) by Taiwan. Officially, therefore, the two observations from Taiwan were the Chinese observations. It meant nearly half the chart was blank until my last few months there.

After three years it was back to the United Kingdom and civil aviation, Preston first then Liverpool. As an Experimental Officer pay was rising to the dizzy heights of around £600 per year. On the early morning shift at Preston Air Traffic Control Centre it was certainly earned. In at 0600 local time, draw up the 700, 500, 300, 200 and 100 mb charts, convert the senior forecaster's surface chart to a 1000 mb chart, grid a 1000–500 mb thickness, produce 12-hour forecast thickness, 500, 700 and 300 mb charts and write out the forecast winds for the Preston Flight Information Region all before 0700. Then there was time for a cup of tea.

Liverpool was less hectic, except on Saturdays in summer (package holidays had started) and at any time when Manchester was closed by fog and Liverpool wasn't. Then we had the little game of guessing where the next aircrew to walk in through the door wanted to go. We were still working on individual route forecasts and personal briefings. Foggy days produced another problem. Smoke control was only just starting and we were still getting the real old pea-soup fogs. In addition there was no Weatherline service and all requests had to be handled personally. We used to decide on the forecast then confine incoming public calls to one line and sit one person by the telephone with the forecast. As fast as the telephone was replaced it would ring again; all through the day if the fog persisted.

Another duty was dealing with the Worcester THUM (Temperature and HUMidity) flight. This was an aircraft ascent done every morning around 0800. The aircraft was a Mosquito equipped with temperature and humidity measuring instruments. It took off from Woodvale, flew to Worcester and then climbed to 300 mb taking readings all the way up. Then it returned to Liverpool with the raw data and we converted them into corrected temperatures and dew-points at standard heights and coded them as a TEMP. Of course there were times when landing at Liverpool was not possible but the THUM pilots always took off anyway and landed where they could (anywhere between Kinloss and St Mawgan or Belfast and the near continent) and telephoned the data to us. They rarely missed a day.

The most difficult forecasts were for flights to Norway. We had quite a lot of these, exchanging ships crews. There were no oil rigs then, so only a few observations were available over the North Sea. If the aircraft had come from Norway the pilot had a much better picture of conditions over the North Sea than we had, but by dint of supplying them with good tea we made sure they always came in for a debriefing. Some of the Norwegian crews threatened to submit my forecasts to the museum of modern art in Oslo on the grounds that they were great examples of imaginative art, even if they were not very good forecasts.

By 1961 things were starting to change. We got a FAX machine and said farewell to our hand-plotted charts and HB pencils. We started to hear about experimental forecast charts produced by one of these new-fangled computer things and I decided that some of the fun was going out of the work. So, when the chance came to move to Bracknell in 1963 with perhaps some computer work, I took the 'if you can't beat them, join them' approach and left forecasting; for ever as it turned out.

Books received

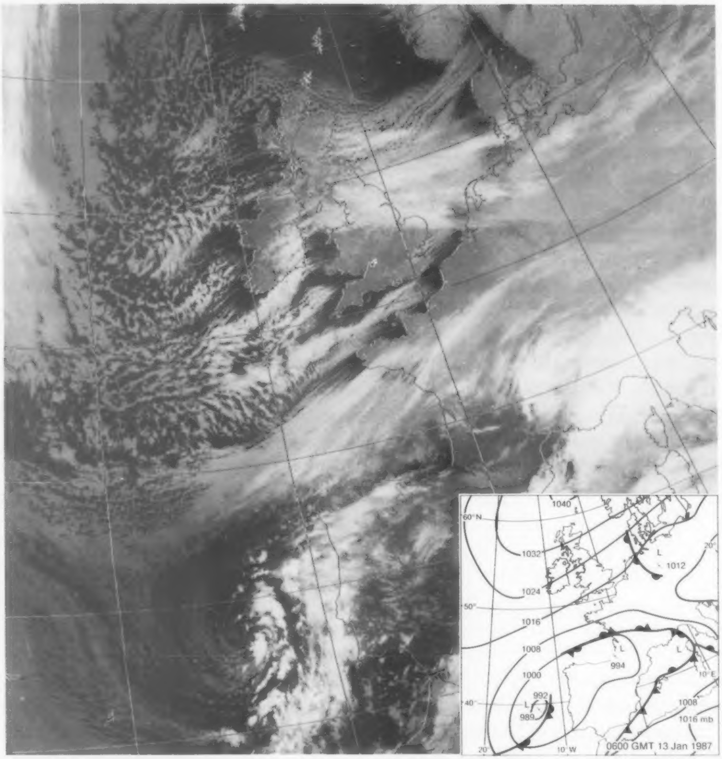
The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

The greenhouse effect, climatic change and ecosystems, edited by B. Bolin, B.R. Döös, J. Jäger and R.A. Warwick (Chichester, New York, Brisbane, Toronto and Singapore, John Wiley and sons, 1986. £56.00) addresses a number of questions which have been of concern in recent years. These include the projection of energy use, increased emission of carbon dioxide and modifications to its cycle, expected increases in other gases in the atmosphere, possible climate change and the overall response of terrestrial ecosystems. Scientists drawn from a number of disciplines contribute to this analysis of these problems.

Satellite photograph — 13 January 1987 at 0359 GMT

This NOAA-9 infra-red image was taken during a period of extreme cold over western and central Europe. Although part of the mainland of Europe is cloud free, convective cloud forms rapidly in the strong east to north-east airflow over the warm waters of the North Sea and the Atlantic Ocean. Over part of the North Sea and the Bay of Biscay, the convection is obscured by upper cloud. A well-defined cyclonic circulation is present off Iberia. The low centre was moving eastwards, and the vigorous convection that can be seen immediately ahead of the vortex lay within an area of positive vorticity advection.

Of particular interest is the pattern of convection to the west of the British Isles, where cloud forms rapidly downwind of significant bays and river estuaries, whilst cloud apparently forms less readily downwind of peninsulas. It is probable that these effects are largely due to land-breezes, although the band downwind of the Strait of Dover (between France and England) is probably at least partly due to coastal convergence, and is very similar in structure to cloud bands observed downwind of the North Channel (between Scotland and Ireland) in cold north-north-westerly outbreaks (Browning *et al.*, *Meteorol Mag*, **114**, 1985, 325–331).



Photograph by courtesy of University of Dundee

Meteorological Magazine

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Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

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